PB83-177659

Methods for Assessing Exposure to Windblown Particulates

Dynamac Corp.
Rockville, MD

Prepared for

Environmental Protection Agency
Washington, DC

Mar 83

U.S. Department of Commerce
National Technical Information Service
NTIS

PB83-177659

EPA-600/4-83-007
March 1983

METHODS FOR ASSESSING EXPOSURE TO WINDBLOWN PARTICULATES

Prepared by

Dynamac Corporation
Enviro Control Division
The Dynamac Building
11140 Rockville Pike
Rockville, MD 20852

Contract No. 68-03-3111

Project Officer

John Schaum
Office of Health and Environmental Assessment
Office of Research and Development
U.S. Environmental Protection Agency
Washington, DC 20460

OFFICE OF HEALTH AND ENVIRONMENTAL ASSESSMENT
OFFICE OF RESEARCH AND DEVELOPMENT
U.S. ENVIRONMENTAL PROTECTION AGENCY
WASHINGTON, DC 20460

REPRODUCED BY
NATIONAL TECHNICAL
INFORMATION SERVICE
U.S. DEPARTMENT OF COMMERCE
SPRINGFIELD, VA. 22161

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

1. REPORT NO.	2.	3. RECIPIENT'S ACCESSION NO.
EPA-600/4-83-007		PB83-177659

4. TITLE AND SUBTITLE	5. REPORT DATE
Methods for Assessing Exposure to Windblown Particulates	March 1983
	6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S)	8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS Dynamac Corporation 11140 Rockville Pike Rockville, MD 20852	10. PROGRAM ELEMENT NO.
	11. CONTRACT/GRANT NO. EPA No. 68-03-3111
12. SPONSORING AGENCY NAME AND ADDRESS Office of Health and Environmental Assessment Office of Research and Development U.S. Environmental Protection Agency Washington, DC 20460	13. TYPE OF REPORT AND PERIOD COVERED Final/June-December, 1982
	14. SPONSORING AGENCY CODE EPA/600/18

15. SUPPLEMENTARY NOTES

16. ABSTRACT This report reviews and evaluates methods for estimating airborne concentrations of particulates originating from waste disposal sites or similar areas over which toxic materials have been intentionally or inadvertently deposited. The purpose of the work is to identify a model (or models) that can be used to estimate human exposure to windblown toxic particulates from contaminated areas. A literature search was conducted and six different particulate suspension or entrainment concepts with possible application to the problem were identified and evaluated: the wind erosion equation, particulate suspension models, resuspension factors, resuspension rates, fugitive dust emission factors, and fugitive dust emission rates. Although all the concepts have been studied extensively, none can satisy all requirements directly, without modification. Recommendations are made to develop preliminary particulate emission rate models for waste disposal sites by adopting existing fugitive dust emission data and using wind erosin equation factors as modifiers. Fully operational dispersion models are available for computing air and surface concentrations of particulates, once the emission rates for waste disposal sites have been estimated. If subsequent use of these preliminary models indicates serious exposures can occur to toxic particulates from hazardous waste sites, then emission rate measurements from toxic waste disposal sites are recommended for the development of more accurate airborne particulate models.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Exposure Models Wind Erosion Windblown particulates Atmospheric Dispersion Models		

18. DISTRIBUTION STATEMENT	19. SECURITY CLASS *(This Report)*	21. NO. OF PAGES
Release Unlimited	Unclassified	63
	20. SECURITY CLASS *(This page)*	22. PRICE
	Unclassified	

EPA Form 2220-1 (9-73)

DISCLAIMER

Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

FOREWORD

The Exposure Assessment Group (EAG) of EPA's Office of Research and Development has three main functions: (1) to conduct exposure assessments, (2) to review assessments and related documents, and (3) to develop guidelines for Agency exposure assessments. The activities under each of these functions are supported by and respond to the needs of the various EPA program offices. In relation to the third function, EAG sponsors projects aimed at developing or refining techniques used in exposure assessments. This study is one of these projects and was done for the Office of Solid Waste and Emergency Response.

Spills, waste disposal, and various industrial operations can result in the contamination of land surfaces with toxic chemicals. Soil particles from these areas can be entrained into the air, transported offsite via the wind, and result in human exposure by direct inhalation. Indirect exposure could result if particulates are deposited in agricultural fields, pastures, or waterways and enter the human food chain. This exposure route is enhanced by the fact that many of the environmentally troublesome compounds are tightly bound to particles and many surface-contaminated sites have conditions favoring wind erosion, such as sparse vegetation cover and high levels of activity which disturb the surface.

The purpose of this report is to (1) present the available methods for estimating mass emission rates and downwind air concentrations of windblown particulates and (2) evaluate their applicability to exposure analysis associated with surface contamination problems.

James W. Falco, Director
Exposure Assessment Group

ABSTRACT

This report reviews and evaluates methods for estimating airborne concentrations of particulates originating from waste disposal sites or similar areas over which toxic materials have been intentionally or inadvertently deposited. The purpose of the work is to identify a model (or models) that can be used to estimate human exposure to windblown toxic particulates from contaminated areas.

A literature search was conducted, and six different particulate suspension or entrainment concepts with possible application to the problem were identified and evaluated: the wind erosion equation, particulate suspension models, resuspension factors, resuspension rates, fugitive dust emission factors, and fugitive dust emission rates.

Although all the concepts have been studied extensively, none can satisfy all requirements directly, without modification. Recommendations are made to develop preliminary particulate emission rate models for waste disposal sites by adopting existing fugitive dust emission data and using wind erosion equation factors as modifiers. Fully operational dispersion models are available for computing air and surface concentrations of particulates once the emission rates for waste disposal sites have been estimated.

If the subsequent use of these preliminary models indicates that serious exposures to toxic particulates can occur from hazardous waste sites, then emission rate measurements from toxic waste disposal sites are recommended for the development of more accurate airborne particulate models.

CONTENTS

		Page
	DISCLAIMER	ii
	FOREWORD	iii
	ABSTRACT	iv
	TABLES AND FIGURES	vi
	ACKNOWLEDGMENTS	vii
I.	INTRODUCTION AND SUMMARY	1
	A. OBJECTIVES AND APPROACH	1
	B. SUMMARY OF REPORT CONTENTS	1
	C. CONCLUSIONS	2
II.	MODEL REQUIREMENTS	3
III.	LITERATURE SEARCH STRATEGY AND RESULTS	6
	A. ONLINE COMPUTER SEARCH	6
	B. TREE SEARCH	6
	C. PERSONAL CONTACT	7
IV.	REVIEW AND EVALUATION OF RELATED WORK	8
	A. OVERVIEW	8
	B. SOIL EROSION MODELS	13
	C. RESUSPENSION MODELS	20
	D. EMISSION RATES	24
	E. DISPERSION MODELS	27
V.	ANALYSIS	30
	A. ENTRAINMENT MODELS	30
	B. DISPERSION MODELS	42
VI.	RECOMMENDATIONS	50
	REFERENCES	52
	TECHNICAL REPORT DATA	57

TABLES AND FIGURES

TABLES

1. Variables That Influence Entrainment by Wind 4

2. Environmental Variables and Model Parameters for the Wind Erosion Equation 15

3. Evaluation of Entrainment Concepts 31

4. Adjusted Soil Erodibility Index 34

5. Measured and Estimated Emission Rates 35

6. The Effects of Windspeed Dependency of Source Strength on Average Downwind Air Concentrations 41

7. Number of Source Widths the Point Source is Located Upwind 48

FIGURES

1. Resuspension factor range from mechanical and wind resuspension stresses 21

2. Resuspension rates and factors as a function of windspeed 23

3. $G_i(x)$ as a function of downwind distance and stability class over rural terrain 46

ACKNOWLEDGMENTS

This report was prepared by Willard W. Perry, the principal investigator, under the program management of Dr. Cipriano Cueto. The literature search and the screening and review of relevant papers were performed by Dr. Janice Longstreth and Gloria Fine.

The draft report was reviewed by Exposure Assessment Group personnel and external reviewers with special expertise in the subjects under investigation.

The authors wish to thank the following reviewers for their thoughtful comments and recommendations, which have been carefully considered and incorporated in this present draft:

James Falco, EPA (EAG)
Dale Gillette, NOAA
Joan Lefler, EPA (OPTS)
John Schaum, EPA (EAG)
W. John Smith, Colo. State U.
James Sutterland, EPA (OAQPS)
Joseph Tikvart, EPA (OAQPS)

I. INTRODUCTION AND SUMMARY

A. OBJECTIVES AND APPROACH

This report is a review and evaluation of methods for estimating airborne concentrations of particulates originating from waste disposal sites and similar areas over which toxic materials have intentionally or inadvertently been deposited. The purpose of the work is to identify a model (or models) that can be used to estimate human exposure to toxic particulates from contaminated areas. The intended use of the model is to assess the toxic particulate inhalation risk to people living in the vicinity of waste disposal sites and other potentially contaminated areas such as landfills, abandoned manufacturing sites, and areas where hazardous materials spills have occurred.

The objective of this study is to make specific recommendations regarding the model that best satisfies exposure assessment requirements. This can be either an existing model or a "new" model involving modifications to existing models. The approach taken to identify the recommended model has involved five steps: (1) the model requirements were clearly defined; (2) a literature search was conducted to identify models or studies with possible application to the problem; (3) all relevant materials found were carefully reviewed and evaluated against the requirements for the model; (4) based on this review and analysis, the model that best fits the requirements was identified; and (5) recommendations for adapting the model to the problem at hand were made.

B. SUMMARY OF REPORT CONTENTS

This report is organized along the lines of the workflow just described. Chapter II elaborates on the model requirements. Chapter III

presents the literature search strategy and results. Chapter IV is the review and evaluation of the relevant studies and models found in the literature and elsewhere. In light of the review in Chapter IV, an analysis of the problem is presented in Chapter V. Finally, Chapter VI presents the specific recommendations of the study, which include the models best suited to the problem and the work required for their implementation.

C. CONCLUSIONS

No models were found that satisfy the study requirements directly, without modification. However, there is considerable work on fugitive dust emissions from a variety of sources that can be used to estimate particulate emissions from waste disposal sites and similar contaminated areas. Also, soil erosion models developed by agricultural scientists are useful in modeling regional and climatic variations in the particulate emissions. Once the emission rates for waste disposal sites are estimated, fully operational plume dispersion models are available for computing air and surface concentrations of particulates in the vicinity of the sites. In addition to the computerized diffusion models, a simplified diffusion model adaptable to the hand calculator is recommended for providing quick and rough assessments of contamination problems.

Although it is believed that with minimal effort a model can be derived to estimate windblown particulate concentrations from waste dumps and other contaminated sites, it is important to note that without field measurements there is no way of determining the accuracy of such a model. It is possible that the model derived by extrapolation from other types of windblown sources could be in substantial error. Consequently, in addition to recommendations for implementing a model by extrapolating from other fugitive dust sources, recommendations are made for particulate measurements as the basis for further development and calibration of the model.

II. MODEL REQUIREMENTS

The desired outputs of the model sought are breathing-level atmospheric concentrations of respirable particles originating from disposal or spill sites as a function of distance from the site. Secondary outputs are surface concentrations of respirable particles. The model is to be used in assessing the long-term risk to people living in the vicinity of areas contaminated by toxic materials; hence, the model must be configured to calculate long-term average concentrations rather than short-term, episodic, or "worst case" concentrations. Also, the model must be site specific, enabling the calculation of concentrations in the vicinity of specific locations in the United States.

There are two basic phenomena to be modeled: (1) entrainment of the particulate matter into the atmosphere and (2) dispersion of the particulate matter once it is entrained. The only entrainment to be considered is that due to wind erosion or to onsite activities such as vehicular travel, dumping, or leveling. The disposition of the suspended particulates is to include atmospheric diffusion, wind transport, fallout, and, if important, resuspension.

There are many parameters used to characterize downwind concentrations due to wind erosion. Table 1 presents the variables affecting wind erosion that have been identified by Sehmel (1980). It is impractical and unnecessary to include most of these variables in the model being developed for various reasons; e.g., their theory is unknown or not sufficiently developed; their influence on the final result is small compared to other factors or unknowns; they are too costly to be included in the model; and their effects are largely averaged out when considering annual concentrations. The fact that there are many parameters affecting the problem in ways that are not well understood is indicative of large uncertainties in estimation techniques, which at best will provide order-of-magnitude estimates. For the present problem, we are to identify the simplest model possible that will provide an accuracy in line with the basic uncertainties that cannot be controlled. For

Table 1. Variables That Influence Entrainment by Wind (Sehmel 1980)

Pollutant Particle Properties	Soil Properties	Particle-Soil Interaction	Surface Properties	Topography	Meteorological Variables
Chemical reactivity	Moisture content	Attraction forces:	Areas of erodible surface	Agricultural	Air density, affected by
Density	Ratio of erodible to nonerodible fractions	• Molecular forces Van-der-Waals forces	Cohesiveness of particles	Broken	• Humidity
Hydrophobic		• Chemical binding forces (Valence forces)	• Binding action of materials	Desert	• Pressure
Hydrophilic					
Particle diameter	Soil size frequency distribution	• Electrostatic forces	• Surface moisture	Diurnal	• Temperature
• Respirable	Specific gravity	• Magnetic forces	Cover	Flat	Soil burden carried
• Nonrespirable	Structure	Capillary forces at the surface of aggregates filled with liquid	Obstructions	Forested	• Influence on air velocity
• Frequency distribution	• Organic matter	Chemical reaction	Roughness, large scale	Hills	• Avalanching
Shape	• Lime content	Contact area effect on adhesion	• Mechanical turbulence	Humidity	• Saltation
Surface roughness	• Texture	• Particle shape	• Overall sheltering	Seasonal	Surface moisture content
	Temperature	• Particle size	Roughness, small scale	Temperature	• Dew
		• Nature of particle and surface	• Orientation of obstacles	Undulating	• Frost upheaval
		• Surface roughness	• Percent of area covered by non-erodible aggregates or obstacles	Uniform	Relative humidity
		• Adhesion of agglomerates vs individual particles	• Sheltering of individual particles	Urban	Temperature
		Crystallization of dissolved substances	• Stability of aggregates against abrasion and disintegration by moisture and watering	Valley	• Surface dry
		Deposition of suspended colloidal particle	Temperature	Water	• Surface drying
		Hardening binders	Topographic features		• Surface frozen
		Liquid bridges	• Broken		• Windspeed
		Mineral bridges	• Uniform		Wind removal forces
		Relative humidity	Vegetative cover		• Mean windspeed
		Temperature	• Live vegetation		• Frequency, period, and intensity of gusts penetrating to the surface
		Time of contact	• Plant residue		• Transient and steady drag
		Viscous surface coating			• Vertical wind profile
					• Stability
					• Vertical turbulent exchange
					• Surface roughness
					• Temperature stratification
					• Wind direction

example, variables that improve the accuracy of the result by only a factor of two are probably not necessary because uncertainties due to terrain, soil characteristics, and meteorologic unknowns will introduce errors of greater magnitude. In any case, the accuracy of the model should be sufficient to allow useful relative comparisons of the exposures from different sites and to enable the identification of the most influential factors. Other requirements regarding the complexity of the model are that the data be easily obtained and the computation time be minimal.

The types of disposal sites of interest are those in which toxic materials have been deposited and/or mixed with surface soil. These include industrial disposal sites such as settling ponds and solid waste landfills; municipal disposal sites used for disposal of chemical wastes; salvage yards used for storing chemical wastes, usually in drums that can leak their contents into the soil; abandoned industrial plants and chemical storage facilities that have the potential for deteriorating to toxic fugitive dust sources; and hazardous material spill sites that are not properly cleaned up. Of principal interest are the pre-RCRA sites in which high concentrations of toxic chemicals are exposed to the wind either directly from the surface (e.g., dried-up settling ponds or spill sites) or as a mixture of soil and waste materials (e.g., landfills). These sites will vary as to (1) the number and type of toxic chemicals (settling ponds are more likely to contain only a few different chemicals whereas municipal landfills and salvage operations could contain many different toxic chemicals); (2) the concentration of the toxic materials, either as an unmixed surface deposit or mixed with other wastes and soil; (3) the age or weathering of the site and the nature of the soil; and (4) the type and frequency of physical activities at the site that can loosen the soil and enhance fugitive dust emissions. For the present task of determining if applicable models are available, specific disposal site characteristics and scenarios have not been defined. Such definition is needed for the implementation and testing of the model, which is beyond the scope of the present study.

III. LITERATURE SEARCH STRATEGY AND RESULTS

A comprehensive literature search for articles relative to the modeling of windblown particulates was accomplished in three phases:

1. Online Computer Search
2. Tree Search
3. Personal Contact

A. ONLINE COMPUTER SEARCH

Twelve databases from three major information systems were accessed in the first phase of the literature search. A total of 691 citations were retrieved for review from the following databases:

NTIS
Enviroline
Pollution Abstracts
Aptic
Environmental Bibibliography
Met/Geoastro
Agricola
Biosis
Life Sciences Collection
CAB Abstracts
Safety
Toxline

B. TREE SEARCH

On completion of the online computer search, the resulting printouts (titles and abstracts) were reviewed and screened for relevancy by two senior scientists, including a systems analyst/model builder. Relevant articles were retrieved and critically reviewed. Additional material was then selected from references and bibliographies of selected articles. Review articles that were particularly valuable for identifying additional articles were Smith et al. (1982), Sehmel (1980), and Slinn (1976).

C. PERSONAL CONTACT

The third phase of the literature search was conducted on the personal level. Scientists working in the field were contacted for their advice and for additional references. Three investigators who were particularly helpful were J. Tikvart and J. Lefler of EPA and W. John Smith of Colorado State University.

IV. REVIEW AND EVALUATION OF RELATED WORK

A. OVERVIEW

There has been a great deal of research on both the entrainment and dispersion of particulates by wind. The entrainment work falls into three areas, each of which employs different theories and techniques to predict the suspension of particulates:

1. Wind erosion research by agricultural scientists for the purpose of predicting soil loss from farmland and developing means of reducing soil loss.

2. Particle resuspension research originally conducted for the purpose of estimating the resuspension of radioactive materials inadvertently deposited on environmental surfaces, which has broadened to include all types of toxic contaminants.

3. Emission rate or emission factor work for the purpose of estimating the rate at which pollutants are injected into the atmosphere from various types of pollution sources.

In the case of the particulate dispersion research, there is little diversity among the various dispersion models with potential application to the present problem; they all use various adaptations of the Gaussian diffusion model. From a practical point of view, the Gaussian diffusion model is the simplest model that will provide reasonable predictions. To increase the prediction fidelity significantly requires efforts far beyond the scope of the present study. There are countless versions and adaptations of the Gaussian diffusion model that vary according to: (1) how the source is represented and integrated, (2) how the averaging is done over the various parameters, and (3) how special features are incorporated such as fallout, deposition, or resuspension. Not all of the different versions were reviewed; rather, one or two models that satisfied the requirements and are fully operational were located, and these are being recommended for consideration for the dispersion portion

of the model. Also being recommended is a simplified version, programmable on the hand calculator, to be used in obtaining quick estimates of possible contamination problems.

With regard to the particulate entrainment and suspension research found in the literature, an overview of each of the three separate research areas is presented below.

1. Wind Erosion Research

The wind erosion research for agricultural interests has resulted in the development of the wind erosion equation, a well-developed empirical model that estimates annual soil loss from agricultural fields in tons per acre, as a function of various field, soil, and climatic factors (Chepil and Woodruff 1963). The equation predicts the total amount of soil eroded by the wind and does not differentiate between suspended matter that is carried downwind and heavy particles that roll or bounce along the surface. This is the principal difficulty in applying the wind erosion equation to predicting soil entrainment from waste disposal sites. Another difficulty is that the correlation between wind erosion from farmland and wind erosion from waste dumps is unknown.

To investigate the contribution that suspension makes to wind erosion, Gillette et al. (1972) studied the wind suspension of agricultural soils and, through a series of measurements, derived an empirical equation (Gillette, 1974) for predicting vertical mass flux (particle suspension rate) as a function of windspeed and soil size distribution. Using Gillette's results and wind erosion theory, three investigators (Mills et al. 1974; Travis 1975; Porch 1979) developed computer models for predicting the entrainment and movement of soil aerosols by the wind. These models predict downwind atmospheric concentrations of wind-suspended particles and would seem to have application to the problem at hand. However, all three models are nonaveraging and predict hourly or short-term concentrations only. Thus,

substantial work is needed to adapt them to the present problem of predicting annual concentrations. Furthermore, the submodels for predicting particle suspension rates ($g/m^2/sec$) are in rudimentary stages of development and have not had sufficient experimental verification.

2. Resuspension Research

The second field of research with possible relevance to predicting the entrainment of particulate matter from waste disposal sites is the resuspension research performed to investigate the hazards of radioactive or toxic materials inadvertently spilled or strewn over the ground. Most of this research consists of experiments in which tracer materials are deposited over soil areas and measurements are taken to determine the resuspension of the contaminants by the wind. In all of this work, the contaminant sources are represented by surface concentrations; e.g., mass per unit area, particles per unit area, curies per unit area, or organisms per unit area.

The experiments are conducted to determine either resuspension factors or resuspension rates. Resuspension factors are the ratios of the contaminant concentrations in air (just over the contaminated surface) to the contaminant concentrations on the surface. Thus, if the resuspension factor is known for a given situation, then one can predict the air concentration of the contaminant, given the surface concentration. It is readily apparent that resuspension factors have no application to the problem because they predict air concentrations over the surface and not downwind. Furthermore, they do not indicate the rate at which the contaminant is being suspended so they cannot be used with a diffusion model to predict downwind concentrations.

The resuspension rate is the fraction of the contaminant suspended per unit of time. Thus, if the resuspension rate is known, the rate at which the contaminant is being suspended (e.g., $g/m^2/sec$) can be predicted by simply multiplying the surface concentration (g/m^2) by the

resuspension rate (sec^{-1}). The rate at which the material is being suspended is precisely the source term needed in diffusion models for the prediction of downwind concentrations. However, to obtain this value from resuspension rates, the contamination must be represented as a surface concentration (e.g., g/m^2). For disposal sites, the contamination generally will be represented as a density (g/m^3) or as a fraction of the soil mass. In either case, resuspension rates cannot be used directly to predict the rate at which the soil or the contaminant in the disposal site is being suspended. However, by making assumptions regarding the depth of soil within which the tracers were deposited and mixed during the resuspension rate experiments, the resuspension rates can be converted to usable parameters. For other types of contamination situations (e.g., spills) the contamination may be represented by a surface density. In these cases, the resuspension rates can be used directly to estimate the rate at which the material is being suspended.

Sehmel (1980) has done a great deal of work with resuspension rates as a function of soil characteristics and windspeed, and has prepared an excellent review of work by himself and others. In related work, Amato (1976) and Hereim and Ritchie (1976) have studied resuspension of material that has been deposited from a primary source. Amato's work is theoretical. He obtained resuspension ratios of the order of 10% to 50%, depending on windspeed and other factors. The resuspension ratio is the ratio of the air concentration caused by resuspension of previously deposited particles to the air concentration arriving directly from a particulate source. Hereim and Ritchie experimentally examined the resuspension of a bacterial aerosol from desert soil and found that the concentration of resuspended bacteria was of the order of only 1% to 3% of that arriving directly from the primary source, even when the resuspension was enhanced by crawling or marching men. Based on this result, it appears that the modeling of resuspension of particulates deposited downwind of the disposal sites is unnecessary.

3. Air Quality Research

The third area of research dealing with the entrainment of suspension of particulates by wind is the air quality and air pollution research on emission rates from various types of sources. Over the past decade, a number of investigators have studied fugitive dust emissions from open sources; i.e., dust that has been entrained by wind erosion or by mechanical activity at the source. Blackwood and Wachter (1978) and Smit (1980) have measured coal dust emissions from coal storage piles. Blackwood et al. (1978) and Cole and McVehil (1977) investigated rock dust emissions from quarry storage piles. PEDCo. (1973) and Cowherd et al. (1974) have developed emission factors for a number of fugitive dust sources including construction sites, agricultural tilling, vehicular movements on unpaved roads, and mineral storage piles. Schwendiman et al. (1979) and Amick et al. (1974) have studied fugitive dust emisions from tailing piles. Ochsner and Blackwood (1977) and Zimmer and Axetell (1978) have investigated fugitive dust from mining operations.

In much of this work, emission rates (mass/area/time) have been (or can be) derived. These rates provide the emission data in the proper form for use with Gaussian diffusion models for predicting downwind concentrations of dust from any size source. In fact, the method used by most of the investigators for estimating the emission factors consists of taking a series of downwind concentration measurements and fitting the data by a Gaussian plume dispersion model to determine the effective emission rate that would yield the measured concentrations.

Although the correlation between emissions from the various sources investigated and emissions from waste disposal sites is unknown, the emission rate work has certain features that make it attractive: (1) it is based on direct measurement of suspended dust concentration; (2) particle size distribution is considered by most investigators, and in

some cases the emission rates are based on measurements of respirable-size particles (i.e., those with a diameter of 7 um or less)*; and (3) the activities at the emission site are taken into account and some emission rates given as a function of the level of activity. In some instances these activities are similar to those expected at waste disposal sites.

Much of the air quality work involves the determination of emission factors rather than emission rates. An emission factor is an estimate of the rate at which a pollutant is released to the atmosphere as a result of some activity divided by the level of that activity. Examples of such emission factors are tons of dust emitted per ton of coal mined, grams of dust emitted per mile of vehicle traveled on unpaved roads, and pounds of dust emitted per acre of farmland tilled. These emission factors are of no use to the present problem unless they can be converted to emission rates in terms of mass per unit of area per unit of time.

In the remainder of this chapter, specific papers and concepts in each of the three areas of particle entrainment research are reviewed and evaluated. The last section of the chapter briefly discusses Gaussian dispersion models.

B. SOIL EROSION MODELS

1. Wind Erosion Equation

Wind erosion modeling represents an early attempt to evaluate movement of particles by air. Soil erosion is, of course, of great agricultural concern because it reduces the fertility of the soil; wind erosion modeling is an attempt to determine just how much soil will be

---

* EPA is considering a revision to the National Ambient Air Quality Standard based on health effects observations of particles with a diameter of 10 um or less.

lost as well as allowing evaluation of modifying parameters such as vegetative cover and climatic factors. Through the work of a variety of researchers (e.g., Chepil and Woodruff 1963; Woodruff and Siddoway 1965; Skidmore 1976), an empirical equation that allows such an assessment of soil loss was developed. This equation, termed the "wind erosion equation," considers 11 primary variables subsumed under five parameters such that the potential annual average soil loss, E (mass/area/time), is calculated as follows:

$$E = f\,(I', C', K', L', V)$$

Table 2 gives the environmental variables and model parameters for the wind erosion equation. The wind erosion equation was designed to estimate soil losses from agricultural fields. It requires information as to field length, soil cloddiness, roughness, vegetative cover, soil moisture, and wind velocity. Most of this information is available as average annual values measured at reference sites across the country. For ease of use, many of the parameters have been compiled by the U.S. Department of Agriculture in the form of tables and nomographs and maps (Skidmore and Woodruff 1968). The reader can easily identify the site of concern and find information on the nearest reference site (county) that can be used as input.

The drawback of the wind erosion equation, at least for the problem at hand, is that it estimates only the net soil loss with no information regarding the respirable or suspended particle sizes. Soil is moved by the wind via one of three modes: surface creep, saltation, or suspension. Surface creep describes the rolling or sliding movement of particles across a surface. These particles generally have a diameter in excess of 1,000 um and are too heavy to be lifted by the wind. Saltation is a term used to describe the hopping and bouncing movement of a particle. These particles are lifted by the wind but are too heavy to

Table 2. Environmental Variables and Model Parameters for the Wind Erosion Equation (Smith et al. 1982)

Primary Wind Erosion Variables	Equivalent Erosion Equation Parameters
Soil erodibility index, I Function of soil particle size distribution; read from a table Knoll erodibility, I_s Function of knoll slope steepness; read from a graph	Soil and knoll erodibility, I' The product of I and I_s
Surface crust stability, F_s	Disregarded - crust is transient
Soil ridge roughness, K_r Function of height, width, and spacing of clods and furrows	Soil ridge roughness factor, K' Estimated by comparison to a set of standard photographs
Annual average wind velocity, v Read from map Surface soil moisture, M Estimated using Thornthwaite's (1931) precipitation-evaporation index	Local wind erosion climatic factor, C' May be calculated but commonly read from maps of C'
Distance across field, D Field width in direction of primary erosive wind Sheltered distance, D_b Calculated from barrier height upwind of field	Field length, L' The difference between D_f and D_b
Quantity of vegetative cover, R' Mass of standing or fallen vegetative residue per unit area Kind of vegetative cover, S Factor related to erosion-reducing effectiveness of residues from different crops Orientation of vegetative cover, K_o Factor relating erosion reduction to standing vs fallen crop residues	Equivalent vegetative cover, V The product of R', S, and K_o

remain airborne, so they fall back to earth. Particles moved by saltation have diameters ranging between 80 and 1,000 um. Suspension is used to describe particles kept aloft by the wind over large distances; it is generally applicable to particles that have a diameter of 80 um or less. Respirable particles are those with a diameter of 7 um or less. Thus the wind erosion equation concerns the movement of a much larger category of particles than would be expected to represent an exposure hazard to humans. It is possible that this equation could be modified in some way to estimate the proportion of soil moved by wind erosion that is suspended and the proportion of suspended particles that are respirable. This again may vary with soil and climatic differences. Sehmel (1980) notes that suspension moves from 3 to 40% by weight; saltation, from 50 to 75%; and surface creep, from 5 to 25%. Estimates of the proportion of suspended particles that are respirable range from 5 to 40%.

In studies of the contribution of suspension to soil movement, Gillette and his coworkers (Gillette et al. 1972; Gillette 1974; Gillette 1976) reported on particle size measurements of suspended soil above eroding agricultural fields. Measurements of the flux of respirable particles were made at two heights above the fields. The difference in the fluxes at the two heights was the vertical flux; i.e., a measure of the rate at which respirable particles are being entrained by the wind. Based on these experimental data, and for similar erosion conditions (i.e., soil moisture, soil cloddiness, surface roughness, and vegetative cover), Gillette (1974) found that two distinct soil types produced vertical soil fluxes F_v (mass/area/time) that obeyed the following equation:

$$F_v = C_v \, (u^*/u^*_t)^{\gamma}$$

where C_v is a proportionality constant, u^* is the drag velocity (cm/sec) measured during erosion, u^*_t is the threshold drag velocity when soil begins to move, and γ is greater than 3 and highly soil

specific. Travis (1976) fit the data of Gillette (1974) and concluded that Υ could be specified as:

$$\Upsilon = (P/3) + 3$$

where P is the mass percentage of particles less than 20 um in diameter in a given soil. C_v, as calculated by Travis (1975) for these soil conditions, is approximately 2×10^{-10} $g/cm^2/sec$. As noted by Smith et al. (1982), Gillette's work resulted in a number of conclusions:

1. Suspension is not measured in the absence of saltation.
2. Size distributions of suspended particles match the particle size distribution of the original soil.
3. Mass flux of suspended particles increases with windspeed.
4. Mass flux is greater over a soil with a larger mass fraction in the suspendable size range.

Also, as pointed out by Travis (1975), despite the fact that suspension is thought to move particles of 50 um or less in diameter, Gillette and his coworkers found that nearly all particles measured were 20 um or less in diameter. In a later study, Gillette and Walker (1977) found that all soils produce a very similar size distribution of particles smaller than 20 um. The quality of the particles produced by a given wind, however, depends greatly on the parent soil.

To use Gillette's equation, it would be necessary to make measurements of the drag velocity and the mass percentage of particles less than 20 um in diameter at each site of concern and determine the proportionality constant under the conditions present at the site. Conceivably, Gillette's data could be substituted when sites are located near to where his measurements were made; however, other sites with other erosion conditions would require fairly intensive study. This makes the use of his equation not an appealing possibility, given the fact that a fairly simple, low data requirement approach is desired.

2. Soil Suspension and Redistribution Models

Mills et al. (1974) were the first to try to use the results of Gillette, together with wind erosion theory, to develop a wind erosion model for estimating air concentrations of particles downwind from an eroding source. Their particular interest was to evaluate the airborne contamination problem from uranium mill tailings piles. They developed a theoretical equation for the saltation rate based on Bagnold's (1941) work. They hypothesized that the rate at which mass is suspended (vertical flux) is proportional to the saltation rate. This agreed with Gillette's findings, and Mills used Gillette's results to estimate the proportionality constant between the suspension rate and the saltation rate. The Gaussian plume equation was then used to calculate ground level air concentrations of dust downwind from the tailings piles. The model was programmed on a computer, and sample calculations were made for downwind dust concentrations during a typical windstorm. Since the model calculates short-term concentrations only, it has limited application to the present problem.

Also using Gillette's results and wind erosion theory, Travis (1975) developed a computer model for describing the redistribution of wind-eroding soil contaminants. Like Mills et al. (1974), he related the vertical (suspended) flux to the horizontal (saltation) flux and modified both Bagnold-Chepil's horizontal flux formulation and Gillette's vertical flux formulation. Gillette's experimental work was used to evaluate certain factors, as noted above. The Gaussian puff was incorporated into the model to calculate downwind air and surface concentrations of gust-generated particles eroded from area sources. A grid network was used to characterize soil and surface conditions, and the movement of soil from and to each grid unit by saltation, suspension, deposition, and resuspension was computed and aggregated to give a detailed time-dependent description of the redistribution of contaminants. Sample calculations were made of the redistribution of radioactive contaminants found at uranium mill tailings piles during a windstorm.

Like the model of Mills et al. (1974) described above, the Travis model computes short-term air and surface concentrations only and consequently has limited application to the problem at hand. Also, the Travis model is much more detailed and complex than needed for estimating downwind particulate concentrations from waste disposal sites and similar contaminated areas.

Other investigators (Porch 1979; Momeni et al. 1979) have developed similar, highly detailed simulations of the wind redistribution of surface contaminants. Like the Travis model, these models go far beyond the scope needed to evaluate contaminants from waste dumps and other similar sites. Furthermore, these models are formulated to give short-term concentrations rather than long-term averages and, consequently, are not considered viable candidates for the model being sought.

3. Organic Component of Windblown Soil Aerosols

Zenchelsky et al. (1976) investigated the total organic carbon (TOC) contained in windblown soil aerosols in Texas as a function of particle size and wind velocity. They found that below 3.4 um the mass fraction of organic carbon increases as particle diameter decreases. Putting these results together with previous work for particles in the range of 5 to 250 um (which showed that TOC increased with particle diameter), the investigators concluded that TOC in windblown aerosols is minimal for particles in the range of 2 to 10 um. A minimum mass ratio of TOC to particulate of 1% or less holds for all wind velocities. These results are of interest because they indicate that the amount of natural organic matter contained in respirable-size particles is small. Although the application of this work to particulates from waste disposal sites is unknown, the results indicate that the mass percentage of the suspended material that is toxic may be a function of particle size.

C. RESUSPENSION MODELS

Sehmel (1980) presents an excellent summary of the resuspension work that has been conducted over the last decade or so. He clearly defines resuspension factors and resuspension rates and tabulates experimental results of many investigations for both.

1. Resuspension Factors

Figure 1 presents Sehmel's (1980) summary of experimental data on both mechanically induced and wind-induced resuspension factors. The resuspension factor (RF) is defined as:

$$\text{RF (units of } m^{-1}) = \frac{\text{airborne concentration } (g/m^3)}{\text{surface concentration } (g/m^2)}$$

The concentrations also can be characterized in units other than grams (e.g., curies or number of particles). It can be seen from Figure 1 that wind-induced resuspension factors range from 10^{-10} to 3×10^{-4} m^{-1} (over six orders of magnitude), and mechanically induced resuspension factors range from 10^{-10} to 4×10^{-2} m^{-1} (over eight orders of magnitude). Resuspension factors are dependent on many parameters, including windspeed, soil characteristics, surface moisture, surface roughness, and type and level of mechanical activity. Sehmel did not try to correlate the resuspension factors to any of these parameters, but a cursory look at the data in Figure 1 indicates that strong correlations are probably not possible. Thus, the value of these data in helping to understand suspension of particles by wind or mechanical activity is limited. As pointed out in the overview earlier, the resuspension factors describe concentrations above the contaminated surface and not downwind, and they cannot be used to model downwind concentrations because they do not indicate the rate at which the particles are suspended. It was thought that they might be used to assist in understanding the dependency of suspension rates on various factors such as type of mechanical activity or soil characteristics. The variance in

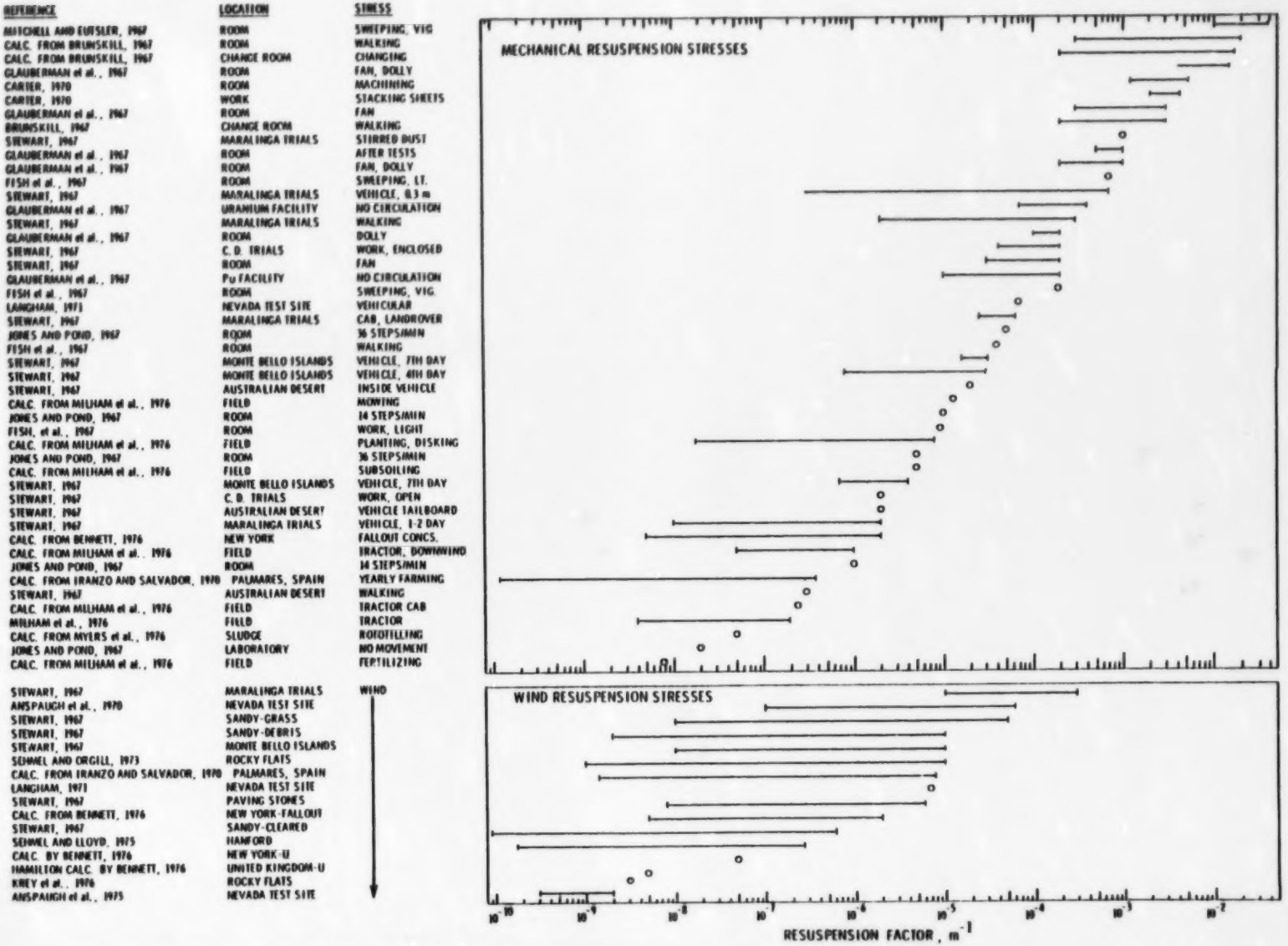

REFERENCE
LOCATION
STRESS
MITCHELL AND EUTSLER, 1967 ROOM SWEEPING, VIG
CALC. FROM BRUNSKILL, 1967 ROOM WALKING
CALC. FROM BRUNSKILL, 1967 CHANGE ROOM CHANGING
GLAUBERMAN et al., 1967 ROOM FAN, DOLLY
CARTER, 1970 ROOM MACHINING
CARTER, 1970 WORK STACKING SHEETS
GLAUBERMAN et al., 1967 ROOM FAN
BRUNSKILL, 1967 CHANGE ROOM WALKING
STEWART, 1967 MARALINGA TRIALS STIRRED DUST
GLAUBERMAN et al., 1967 ROOM AFTER TESTS
GLAUBERMAN et al., 1967 ROOM FAN, DOLLY
FISH et al., 1967 ROOM SWEEPING, LT.
STEWART, 1967 MARALINGA TRIALS VEHICLE, 0.3 m
GLAUBERMAN et al., 1967 URANIUM FACILITY NO CIRCULATION
STEWART, 1967 MARALINGA TRIALS WALKING
GLAUBERMAN et al., 1967 ROOM DOLLY
STEWART, 1967 C. D. TRIALS WORK, ENCLOSED
STEWART, 1967 ROOM FAN
GLAUBERMAN et al., 1967 Pu FACILITY NO CIRCULATION
FISH et al., 1967 ROOM SWEEPING, VIG.
LANGHAM, 1971 NEVADA TEST SITE VEHICULAR
STEWART, 1967 MARALINGA TRIALS CAB, LANDROVER
JONES AND POND, 1967 ROOM 36 STEPS/MIN
FISH et al., 1967 ROOM WALKING
STEWART, 1967 MONTE BELLO ISLANDS VEHICLE, 7TH DAY
STEWART, 1967 MONTE BELLO ISLANDS VEHICLE, 4TH DAY
STEWART, 1967 AUSTRALIAN DESERT INSIDE VEHICLE
CALC. FROM MILHAM et al., 1976 FIELD MOWING
JONES AND POND, 1967 ROOM 14 STEPS/MIN
FISH, et al., 1967 ROOM WORK, LIGHT
CALC. FROM MILHAM et al., 1976 FIELD PLANTING, DISKING
JONES AND POND, 1967 ROOM 36 STEPS/MIN
CALC. FROM MILHAM et al., 1976 FIELD SUBSOILING
STEWART, 1967 MONTE BELLO ISLANDS VEHICLE, 7TH DAY
STEWART, 1967 C. D. TRIALS WORK, OPEN
STEWART, 1967 AUSTRALIAN DESERT VEHICLE TAILBOARD
STEWART, 1967 MARALINGA TRIALS VEHICLE, 1-2 DAY
CALC. FROM BENNETT, 1976 NEW YORK FALLOUT CONCS.
CALC. FROM MILHAM et al., 1976 FIELD TRACTOR, DOWNWIND
JONES AND POND, 1967 ROOM 14 STEPS/MIN
CALC. FROM IRANZO AND SALVADOR, 1970 PALMARES, SPAIN YEARLY FARMING
STEWART, 1967 AUSTRALIAN DESERT WALKING
CALC. FROM MILHAM et al., 1976 FIELD TRACTOR CAB
MILHAM et al., 1976 FIELD TRACTOR
CALC. FROM MYERS et al., 1976 SLUDGE ROTOTILLING
JONES AND POND, 1967 LABORATORY NO MOVEMENT
CALC. FROM MILHAM et al., 1976 FIELD FERTILIZING
STEWART, 1967 MARALINGA TRIALS WIND
ANSPAUGH et al., 1970 NEVADA TEST SITE
STEWART, 1967 SANDY-GRASS
STEWART, 1967 SANDY-DEBRIS
STEWART, 1967 MONTE BELLO ISLANDS
SEHMEL AND ORGILL, 1973 ROCKY FLATS
CALC. FROM IRANZO AND SALVADOR, 1970 PALMARES, SPAIN
LANGHAM, 1971 NEVADA TEST SITE
STEWART, 1967 PAVING STONES
CALC. FROM BENNETT, 1976 NEW YORK-FALLOUT
STEWART, 1967 SANDY-CLEARED
SEHMEL AND LLOYD, 1975 HANFORD
CALC. BY BENNETT, 1976 NEW YORK-U
HAMILTON CALC. BY BENNETT, 1976 UNITED KINGDOM-U
KREY et al., 1976 ROCKY FLATS
ANSPAUGH et al., 1975 NEVADA TEST SITE
MECHANICAL RESUSPENSION STRESSES
WIND RESUSPENSION STRESSES
RESUSPENSION FACTOR, m⁻¹

Figure 1. Resuspension factor ranges from mechanical and wind resuspension stresses (Sehmel 1980).

the results as tabulated by Sehmel suggests that the resuspension factor work is not useful for this purpose.

2. Resuspension Rates

Resuspension rates are defined as the fraction resuspended per unit of time, where the "fraction resuspended" is the fraction of the contaminant previously deposited on the surface that is reentrained into the air. Thus, the vertical flux from a contaminated surface is given by $F_v = RS$, where R is the resuspension rate in sec^{-1} and S is the surface concentration of contamination per unit of area.

Resuspension rates will be highly dependent on the physical form of the contaminant, the characteristics of the surface, the time since the contaminant was deposited on the surface, the windspeed, and many other factors. Thus, as in the case of resuspension factors, resuspension rates would be expected to vary greatly.

Sehmel conducted resuspension rate measurements over several years. He found that for respirable particles, resuspension rates ranged from 2×10^{-10} sec^{-1} to 2×10^{-7} sec^{-1}. (These measurements were all taken in lightly vegetated portions of the Hanover area; other soil and weather conditions would be expected to give different results.) Sehmel (1980) found experimental resuspension rate measurements from various investigators that ranged between 10^{-12} and 10^{-4} fraction of source resuspended per second.

Resuspension rates are generally measured using controlled tracer sources. Figure 2 gives some well-behaved measurements by Sehmel and Lloyd (1975) taken over a 4-month period in a lightly vegetated area. Resuspension of an inert submicrometer tracer placed on the ground in a circle with a radius of 22.9 m was measured. At the circle's center, airborne concentrations were measured to heights of 6.1 m. The measured resuspension rates were a function of the wind velocity and varied between 2×10^{-10} and 2×10^{-8} fraction of source resuspended per

second. For windspeeds greater than 3.6 m/sec, resuspension rates increased with windspeed to the 6.5 power. For comparison, Sehmel and Lloyd computed resuspension factors and plotted them alongside the resuspension rates in Figure 2. This comparison shows that resuspension factors vary with windspeed much the same as do resuspension rates.

3. Resuspension Ratios

Hereim and Ritchie (1976) performed field tests with bacterial tracers to determine how downwind resuspended concentrations compare with concentrations from the primary source. The ratio of resuspended concentration to primary concentration is called the resuspension ratio.

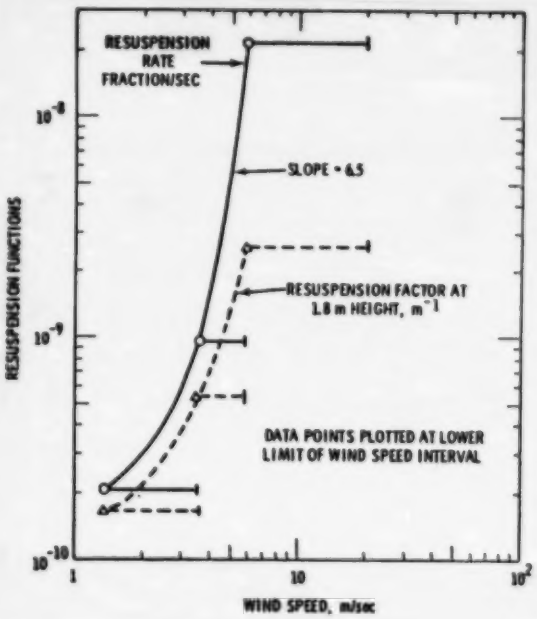

RESUSPENSION RATE FRACTION/SEC
SLOPE = 6.5
RESUSPENSION FACTOR AT 1.8 m HEIGHT, m⁻¹
DATA POINTS PLOTTED AT LOWER LIMIT OF WIND SPEED INTERVAL
RESUSPENSION FUNCTIONS
WIND SPEED, m/sec

Figure 2. Resuspension rates and factors as a function of windspeed (Sehmel 1980).

Resuspended aerosol concentrations were found as far downwind as 3,200 m from the primary aerosol source. However, the resuspension ratios of the aerosol concentrations were less than 0.03, indicating that the resuspended aerosol concentrations were less than 3% of the primary aerosol concentrations. In these experiments, resuspension was enhanced by troop activities that included crawling, marching, and riding in

trucks through the area in which the primary aerosol was deposited. These results indicate that resuspended contaminants that are deposited downwind of a waste disposal site are too small to be of concern.

D. EMISSION RATES

Emission rates were originally derived for smokestacks and other urban point sources of pollutants to enable assessment of air quality in urban areas. The concept has been applied to fugitive dust sources, and, over the past decade, research has been conducted to derive emission rates for a variety of fugitive dust and related sources that generate particulate air contamination in rural as well as urban areas. Thus the term "emission" applies to wind and mechanical generation of aerosols as well as to the factory generation of air pollutants.

The emission rate (mass per unit of time for a point source, or mass per unit of area per unit of time for an area source) is the source term for the Gaussian plume dispersion models that predict downwind pollutant concentrations on a short-term or long-term average basis. In fact, most emission rates are experimentally determined by taking downwind concentration measurements and fitting them to the Gaussian plume model to infer the source strength. Depending on how the measurements are taken over time and averaged, either short-term (1 hour or 24 hours) or long-term average emission rates are derived.

Emissions from fugitive dust sources can be caused by either wind erosion or man's activities at the source; generally both are involved. Emission rates are dependent on windspeed and soil characteristics (and other factors), and some investigators have determined emission rates as a function of windspeed, soil moisture content, and the level of mechanical activity at the site. These effects have been treated either on a short-term, direct-dependency basis or on a long-term average basis.

Cowherd et al. (1974) studied emissions from four types of fugitive dust sources: unpaved roads and airstrips, agricultural tilling,

construction sites, and aggregate storage piles. For all of these sources, emission factors were derived rather than emission rates. For example, for unpaved roads the emission factor derived was in units of pounds per vehicle-mile traveled. However, for aggregate storage piles (gravel and stone stockpiles) emission rates can be extracted from the data presented. For storage piles involving 8-12 hours of activity for a 24-hour period, an emission rate of 13.2 pounds per acre of storage per day was measured. For inactive days, when wind erosion was the only source of particulates, the emission rate was 3.5 pounds per acre of storage per day. The particle sizes for these emissions were not specified. The investigators found no correlation with windspeed but did find a correlation with moisture content of soil storage pile and related the emissions to Thornthwaite's precipitation-evaporation index (P-E).

Amick et al. (1974) tabulates emission factors for a number of fugitive dust sources. For one of the sources, quarrying and mining, emission rates were presented. These rates were derived from previous work by PEDCo (1973). The emission rate for quarrying, mining, and tailings is expressed as:

$$E = 0.133\ C \text{ ton/acre/year}$$

where C is the climatic factor in the wind erosion equation. The factor is given by

$$C = 34.5 \frac{V^3}{(P-E)^2}$$

where V is the mean annual wind velocity in mph, and P-E is Thornthwaite's precipitation index; i.e., an index of equivalent moisture in surface soil particles. Climatic factor maps have been prepared for most areas of the United State (Skidmore and Woodruff 1968). Climatic factors vary from values of below 10 in the East and Southeast to values of over 100 in the Plains States and Southwest. For this range of climatic factors the emission rates from tailings piles become:

C	Emission Rate (tons/acre/year)
1	0.133
10	1.33
100	13.3

Cole and McVehil (1977) measured particulate concentrations from sand and gravel mine storage piles over a 2-year period and compared measured concentrations to those calculated using various Gaussian plume models. They used Cowherd's work (1974) to estimate the average emission rate for the storage piles and predicted downwind air and surface concentrations using six different Gaussian plume models. For the most part, the predicted and measured particulate concentrations differed by less than a factor of two for all models and measurement sites. These results lend credence to the emission rate-Gaussian plume method of predicting downwind particulate concentrations from fugitive dust sources. From particle size measurements of the storage piles, Cole and McVehil estimated that about 30% of the entrained dust was less than 7 um in diameter; i.e., of respirable size.

Smit (1980) measured dust concentrations originating from coal stockpiles in Germany and in the United States. He derived emission rates by fitting the measured data to a Gaussian dispersion model. His results are summarized as follows:

Country	Type of Surface	Emission Rate ($ug/m^2/sec$)
Germany	Fresh base coal surface	1,000
	Old surface	10
United States	Light activity	40
	Moderate activity	100

Smit attributed the emission rate differences between the two countries to be due to the characteristics of the coal; i.e., the amount of fines in German coal was much higher than in U.S. coal. Smit also examined the effects of windspeed and found that the emission rate increased linearly with wind velocity. For size distribution he found that about 35% of the particles by weight were less than 7 um in diameter.

Other investigators have measured emission factors and rates from quarry operations (Blackwood and Wachter 1978) and tailings piles (Schwendiman 1979). No measurements of emissions from general refuse piles or landfills were found.

E. DISPERSION MODELS

The theory and use of Gaussian diffusion models to predict the transport and dispersion of gases and particulates is well covered by Slade (1968) and Turner (1970). Based on this theory, many investigators have developed computer models of various versions of the Gaussian diffusion model to address particular pollution problems. Examples of these are:

- Air Quality Display Model--estimates annual arithmetic average sulfur dioxide and particulate concentrations at ground level in urban areas for point and area sources.
- Gaussian Plume Multiple Source Air Quality Algorithm (RAM)--a steady-state plume model for estimating concentration of pollutants for averaging times of an hour to a day from point and area sources.
- Single Sources (CRSTER) Model--uses a steady-state Gaussian plume formulation for rural and urban point sources in uneven terrain to determine maximum concentrations over 1- and 24-hour periods and to determine the meteorological conditions that cause the maximum concentrations.
- Atmospheric Transport Model (ATM)--developed by Oak Ridge for predicting short- and long-term air and surface concentrations of contaminants from multiple point, line, and area sources in rural terrain.

- Industrial Source Complex (ISC) Model--for predicting long-term average pollutant concentrations from multiple point and area sources in urban or rural terrain.

Under UNAMAP (Users Network for Applied Modeling of Air Pollution) EPA makes available a series of dispersion models for predicting air or surface concentrations of pollutants for various situations and concerns. CRSTER and ISC are 2 of the more than 11 models contained in this service.

Two dispersion models that satisfy the requirements for the present problem have been identified. These are Oak Ridge's ATM and EPA's ISC models. Their capabilities are discussed in Chapter V.

A few points about the theory and use of Gaussian diffusion models are summarized here to provide the basis for understanding the recommendations made later in this report. In the Gaussian theory, the movement of suspended particles and gases by diffusion is characterized by three diffusion coefficients: σ_x, σ_y, and σ_z, where x represents the downwind direction and y and z represent crosswind and vertical directions, respectively. These diffusion coefficients are functions of the atmospheric stability as defined by six atmospheric stability coefficients, A through F, where A is the least stable and F is the most stable. Tables and graphs are available (e.g., from Turner 1970) that give the values of the diffusion coefficients as a function of downwind distance and stability class. Also, mathematical representations of the diffusion coefficients have been derived for use in computer modeling of diffusion.

When considering a steady-state source driven by the wind, a plume is formed and the diffusion coefficient in the direction of the wind, σ_x, is not needed to characterize the diffusion. For long-term average concentrations, use is generally made of the 16-sector wind rose to provide frequencies of windspeeds and wind directions needed to do the averaging. In this long-term averaging, the diffusion in the y direction

is generally integrated from $-\infty$ to $+\infty$ and averaged over the width of the sector containing the receptor of interest. After this averaging, the only diffusion parameter remaining is the vertical diffusion coefficient, σ_z, which is a function of the downwind distance x. The differences between rural and urban diffusion are due to differences in σ_z for rural and urban terrain. Time averaging is done by computing the concentrations at the receptor for each windspeed and stability class, multiplying by the respective windspeed and stability class frequencies, and then summing.

V. ANALYSIS

In reviewing the literature on windblown particulate models, no model was found that could be applied directly to waste disposal sites without some modifications and additional work. At this point, the solution appears to be to select the entrainment concept that is best suited to meet the needs of the problem, adapt it to the prediction of particulate emissions from waste dumps and other contaminated sites, and then combine it with a suitable dispersion model that is fully operational and does not need to be modified. This chapter evaluates the various entrainment and dispersion models that have been identified and analyzes what should be done to adapt them to the problem at hand.

A. ENTRAINMENT MODELS

1. Evaluation of Entrainment Concepts

The literature search identified six different entrainment concepts with possible relevancy to the problem. These are evaluated in Table 3. With one exception, there has been a great deal of field experimentation with each of the concepts.

The wind erosion equation has several attractive features; however, it has one major deficiency that seriously lessens its value. The fraction of eroded soil suspended has not been investigated to the extent needed to use the model to predict suspension rates. The fraction will depend on soil type and other factors and varies from a few percent to as high as 40%. In addition, there is uncertainty as to what fraction of the suspended soil is composed of respirable particles. Thus, until a better understanding is available of these fractions, the wind erosion equation will not give sufficiently accurate estimates of the respirable particle suspension rates to be useful by itself. However, as several

Table 3. Evaluation of Entrainment Concepts

Entrainment Concept	Description of Concept	Relevancy to Problem	Limitations/Drawbacks	Major Needs
Wind erosion equation	Computes wind erosion of farmland in tons/acre/year. Well-developed tables, graphs, and equations allow it to be applied to any area in the United States.	Can be used to estimate wind erosion of waste disposal sites Is a site-specific model that takes into account the weather and soil characteristics of the site Gives annual (rather than short-term) predictions Is easy to use	Does not differentiate between suspended and unsuspended wind erosion Correlation between erosion from farmland and erosion from waste disposal sites is unknown.	Fraction of total that is eroded as suspended particulate in the respirable particle size range
Semiempirical suspension models by Gillette, Mills, Travis, and Porch	Computes rate of suspension of particulates as a function of wind velocity and various other parameters based on wind erosion theory. Mills, Travis, and Porch models also utilize Gaussian dispersion models to predict short-term downwind concentrations.	Can be used to estimate rate of suspension of particulates from waste disposal sites Mills, Travis, and Porch models can be used to predict short-term downwind concentrations from disposal sites.	Semiempirical entrainment models are not sufficiently well founded on experimental data. Must be integrated over time and other parameters to give annual average suspension rates	Experimental verification and further model development Considerable work to adapt model to give annual averages
Resuspension factors	Predicts contaminant concentrations in air due to wind entrainment given the surface concentration of the contaminant	N/A	Does not give rate of entrainment Gives concentrations above emitting surface and not downwind	Cannot be adapted to problem
Resuspension rates	Predicts rate at which contaminants are suspended given the surface concentrations of the contaminant; e.g., mass of the contaminant per unit of area	Can be used to predict particle entrainment rates for disposal site if surface concentrations of the contaminant are known or if assumptions are made as to the depth of the contaminant deposited during original experiment	Unless surface concentrations are known, does not give suspension rates directly for disposal sites without making critical assumptions that can introduce large errors Measured resuspension rates are inconsistent and vary over several orders of magnitude.	Careful analysis of experiments to determine depth of soil within which tracers are deposited during original experiment Analysis of the existing resuspension rates in light of the above to eliminate inconsistencies in results
Emission factors	Predicts rate of dust emission given some measure of activity of the source (e.g., tons of coal mined)	N/A	Does not give emission rates in units that are applicable to problem	N/A
Emission rates	Predicts rate of particulate emissions in mass per unit of area per unit of time for different kinds of fugitive dust sources	Can be used to estimate dust emission rates for disposal sites	No emission rates exist for waste disposal sites. Applicability of emission rates from other sources is unknown.	Determination of the correlation of existing emission rates to waste disposal sites

investigators (e.g., Cowherd et al. 1974; Amick et al. 1974) have shown, certain aspects of the wind erosion equation can be useful in predicting how suspension rates vary with soil characteristics and climatic factors.

The particle suspension models of Gillette, Mills, Travis, and Porch are largely unproven models and as such are not recommended for predicting particle suspension from waste disposal sites. Just as importantly, the models predict instantaneous suspension rates rather than annual averages and considerable work would be needed to convert them.

Although there has been a considerable amount of work on the experimental determination of resuspension rates, the concept has two main drawbacks. First, to apply the work to the general problem of particulate entrainment from disposal sites, assumptions must be made that can introduce considerable error. Second, the inconsistencies in the published results lead us to question the validity of resuspension rates; e.g., Sehmel (1980) shows resuspension rates varying over eight orders of magnitude. Substantial analysis and additional research are needed to determine how these rates can be applied to waste disposal sites in a meaningful way. Consequently, the resuspension rate model is not recommended for predicting particulate entrainment from waste disposal sites.

For completeness, Table 3 lists emission factors. These factors predict emissions as a function of some activity parameter of the source such as tons of coal mined or car miles traveled. Since these activities cannot be related to waste disposal site activities, these types of emission factors are not applicable.

The value of emission rates is that they are based on the direct measurement of downwind particulate concentrations from specific fugitive dust sources. Thus, they are less likely to be in error than the other entrainment models. The two principal deficiencies are: (1) since emission rates do not exist for waste disposal sites, extrapolations from

other types of fugitive dust sources must be made, and (2) their dependency on windspeed and other factors is not clearly understood. Nevertheless, all things considered, and in the absence of field measurements, emission rates are believed to provide the most accurate means of predicting the fugitive dust emissions from waste disposal sites.

What is needed is a careful correlation of the characteristics of measured fugitive dust sources with those of waste disposal sites in order to best estimate emission rates for the waste disposal sites. In this correlation, the wind erosion equation data could be useful. For example, the soil erodibility index for sand is seven times that for clay (see Table 4). Thus, if the emission rate measurements were made for a sandy soil and the waste disposal operations are in clay, then the wind erosion data would suggest that the soil emission rates be adjusted downward when applied to these particular waste disposal operations. Cowherd et al. (1974) and Amick et al. (1974) have derived methods that show the dependency of emission factors on regional variations such as soil characteristics and climatic conditions. These methods were derived for emissions from agricultural tilling and quarry operations, but they could very well apply to waste disposal sites. Cowherd's measurements show that the emissions from agricultural tilling are proportional percentagewise to the silt content of the soil. Amick's work shows that emissions from quarry operations vary linearly with the climatic factor used in the wind erosion equation. The climatic factor accounts for variations in mean windspeed and in soil moisture content. This work should be applicable to waste disposal site emissions to account for regional variations, and we recommend that it be incorporated in the model.

Table 4. Adjusted Soil Erodibility Index (Evans and Cooper 1980)

Soil Types	Adjusted Erodibility Index (tons/acre/yr)
Sand	436
Loam	207
Loamy-sand	180
Sandy-loam	156
Sandy-clay-loam	129
Silt-loam	91
Clay, silty-clay	60
Silty-clay-loam	59
Clay-loam	44
Sandy-clay	31
Silt	11

2. Preliminary Analysis of Emission Rates

Emission rates measured or estimated by various investigators are presented in Table 5. Also presented for comparison are "emission rates" inferred from resuspension rate measurements and from the wind erosion equation. The right-hand column gives emission rates of respirable-size particles. When measurements were for total particulates, use was made of measured soil particle distributions to estimate the fraction of the total that is of respirable size. Gillette (1972) and other investigators have shown that the suspended particle distribution is similar to the particle distribution of the soil.

In the case of Cowherd's and Amick's data, it was assumed that 30% of the total emissions was of respirable size. This value corresponds to the findings of Cole and McVehil (1977) for similar fugitive dust sources. For converting wind erosion equation data to respirable particles, it was assumed that 1% of total soil eroded by the wind resided in the respirable range. This is based on the assumption that 3% of the total is suspended (Sehmel 1980) and, of that, 30% is of respirable size.

Table 5. Measured and Estimated Emission Rates

Investigator	Experiment	Fugitive Dust Source	Results	Emission Rate (E) for Respirable Size Particles
Cole & McVehil (1977)	Measured dustfall from mine operations over 3-month period and calculated average concentrations and compared them to predicted concentrations using Cowherd's method of calculating source strength	Rock dust from active quarry storage piles with load-in and load-out activities	Predicted concentrations within a factor of two are measured; 30% of dust in respirable size particles	$E = 6\ ug/m^2/sec$
Gillette (1972)	Used jet impactors to measure vertical flux from eroding field in respirable size particles	Agricultural field in Nebraska; lightly vegetated	Measured vertical flux at 3 velocities	4-10 m/sec $E = 1\ ug/m^2/sec$ 11 m/sec $E = 0.09\ ug/m^2/sec$ Low windspeed (plowing upwind) $E = 0.06\ ug/m^2/sec$
Smit (1980)	Measured dust concentrations from coal piles and estimated source strength from measurements	Coal dust from fresh and crusted coal piles in Germany (fine coal dust) and from coal piles in U.S. (coarse coal dust)	Fresh bare coal pile $E_T = 10^{-3}\ g/m^2/sec$ Crusted surface $E_T = 10^{-5}\ g/m^2/sec$ Light activity $E_T = 4 \times 10^{-5}\ g/m^2/sec$ Moderate activity $E_T = 1 \times 10^{-4}\ g/m^2/sec$	Fresh bare coal pile, no activity (Germany) $E = 300\ ug/m^2/sec$ Crusted old surface (Germany) $E = 3\ ug/m^2/sec$ Light Activity (U.S.) $E = 12\ ug/m^2/sec$ Moderate Activity (U.S.) $E = 30\ ug/m^2/sec$
Cowherd et al. (1974)	Measured emission rates of aggregate storage piles	Active and nonactive rock and gravel storage piles	Respirable size particles (30%) Active (load in and out) $E_T = 13.2$ lbs/acre/day Inactive (wind erosion) $E_T = 3.5$ lbs/acre/day	Active $E = 5.2\ ug/m^2/sec$ Inactive $E = 1.4\ ug/m^2/sec$ (Assumed 30% in respirable size)

Table 5. Measured and Estimated Emission Rates (Continued)

Investigator	Experiment	Fugitive Dust Source	Results	Emission Rate (E) for Respirable Size Particles
Amick et al. (1974)	Predicted emission rates from quarry operations as a function of climatic factor	Dust from quarrying, mining, and tailings piles	Climatic factor = 10 (East Coast) E_T = 1.33 tons/acre/year	Climatic factor = 10 E = 3 ug/m^2/sec
			Climatic factor = 100 (Kansas) E_T = 13.3 tons/acre/year	Climatic factor = 100 E = 30 ug/m^2/sec (assumed 30% is respirable size particles)
Sehmel & Lloyd (1974)	Particle resuspension rates measured during 4-month period on Hanover Reservation	Respirable tracers/particles from lightly vegetated reservation	Measured resuspension rates for various wind velocities. Average resuspension rate over 4-month period: R = 10^{-10}/sec	E = 2.5 ug/m^2/sec (E = dR assumed d = 1 cm)
Evans & Cooper (1980)	Adjusted wind erodibility index	Loamy-sand soil	180 tons/acre/year	E = 13 ug/m^2/sec
		Silt loam soil	91 tons/acre/year	E = 6 ug/m^2/sec
		Clay-loam soil	44 tons/acre/year (E_T = 7.2 A ug/m^2/sec when A is in tons/acre/year)	E = 3 ug/m^2/sec (assumed 1% of wind erosion is in respirable size particles)

The resuspension rate data were converted to emission rates assuming the tracer Sehmel used in his experiments was mixed with the soil to a 1-cm depth (Sehmel's assumption).

Of the emission measurements, the only one that does not compare well is the Smit (1980) measurement for coal dust from a fresh coal pile in Germany. It is about two orders of magnitude higher than Cole and Vehil's (1977) results and those that Smit obtained in the United States. This could be due to the nature of the German coal dust, which was found to be much finer than U.S. coal dust.

Gillette's measurements yield emission rates that are less than those yielded by the coal dust or rock quarry measurements. This is probably due to the fact that the field was lightly vegetated and no farming activity was occurring during the two high wind measurements. When the Sehmel and Lloyd resuspension rate data and the adjusted wind erodibility index are converted to emission rates, the results compare well with the other emission rate data.

Based on this analysis of the limited emission data examined, it appears that annual average respirable particle emission rates in the range of 1 to 30 $ug/m^2/sec$ are found for stone, rock, coal storage piles, and, possibly, farms. Additional emission rate data need to be examined before the emission rates for waste disposal sites and other similar contaminated areas can be estimated.

3. Analysis of the Key Variables Affecting Emission Rates from Waste Disposal Sites

The amount of particulate matter entrained by the wind is determined by the windspeed, the characteristics of the surface, the aerodynamic influences surrounding the site, and the mechanical activities taking place at the site. Of these, the effects of the surface characteristics are the most difficult to understand and predict. The surface characteristics

and their influence on entrainment are a function of the type of soil, the type and amount of chemicals and other wastes mixed with the soil, the age of the surface (how long since last disturbed), the weathering of the surface (sun, temperature, and precipitation effects), the moisture content of the soil, the roughness of the surface, and many other physical and chemical properties of the soil. There has been insufficient research to predict accurately how each of these surface characteristics will affect emission rates from waste disposal sites, and the only way they can be handled practically is in aggregate fashion, as done in the wind erosion equation.

In general, there are two types of surfaces that are characteristic of waste disposal sites: (1) surfaces in which the disposed chemicals are the predominant component, as in undisturbed settling ponds, and (2) surfaces in which soil is a major component, as in landfills or spills. In both of these the cohesion of the surface as determined by both the weathering and the deposited chemicals would have a very strong influence on entrainment. For the latter type of surface, in which soil is a major component, it would seem that the soil erodibility index of the wind erosion equation could be used to predict relative entrainment between sites having different soils. To use the soil erodibility index for the area in which the chemicals themselves are the principal component of the surface, an analysis must be made to determine the type of soil that most closely matches the chemical surface.

The climatic factor of the wind erosion equation predicts the average influence of wind velocity and surface soil moisture on wind erosion for different regions of the United States. This factor has been used by Amick et al. (1974) to estimate regional variations in emission rates due to weather differences. We feel it can be used in the same way for waste disposal site emissions.

In summary, the factors that are available and practical for modeling the effects of weather and surface characteristics on emission rates are:

- Soil erodibility index (predicts the effect of soil type)
- Climatic factor (predicts the effect of regional variables in soil moisture content and wind velocity).

4. Analysis of the Need to Model Windspeed-Dependent Emission Rates

The resuspension and emission research has shown that the entrainment of particulates by wind is strongly dependent on wind velocity. Experiments have been conducted that show that fugitive dust emission rates and resuspension rates increase with windspeed to the nth power, where values for n have been reported as low as 1 (Smit 1980) and as high as 13.5 (Sehmel 1980). Most of the research shows that the emission or resuspension rates increase with windspeed to a power in the range of 3 to 6 (Blackwood and Wachter 1977; Gillette 1978; Bagnold 1941; Gillette 1974; Sehmel and Lloyd 1975). The moisture content and cohesion of the soil greatly affects the windspeed dependency. Mechanical activity at the source that stirs up the dust will also affect the windspeed dependency, which could be the reason Smit found a linear relationship between emission rates and windspeed for coal stockpiles.

The dependence of emission rates on windspeed strongly suggests that the entrainment model recommended for waste disposal sites should take windspeed effects into account. This would mean that the source term Q, used in the dispersion model, would be an explicit function of windspeed. However, there are several reasons why this is not being recommended at this time. First, the windspeed dependency is a function of many parameters (e.g., soil looseness, particle size, moisture content, mechanical activity at the site) that vary over the years in ways that are difficult to estimate and for which data are not available. Thus, an average windspeed dependency would have to be used and there is no way of determining at this time whether one should use a power of 1, 2, 3, or more for this average. Thus, in lieu of modeling emission rates as a function of windspeed, it would be more accurate to

use emission rates derived from measurements of particulate levels that have been taken over a long period of time (e.g., several months). These emission rates would provide realistic averaging over the various soil moisture and windspeed conditions. Hence, in extrapolating emission rates to waste disposal sites, particular attention should be paid to those emission rates that represent averages over time.

The second reason a windspeed-dependent emission rate is not being recommended is that the use of an average (constant) emission rate rather than a wind-dependent emission rate with the dispersion model will not introduce large errors in the result. To illustrate this, consider that the average emission rate for a particular source has been determined and over a 3-day period 100 g is emitted. Now let us suppose on the first day the wind blows at 2 m/sec, on the second at 4 m/sec, and on the third at 8 m/sec. What will the average downwind air concentrations be if we assume different windspeed dependencies for the source strengths? Let $Q_i = KU_i^a$, where Q_i is source strength on day i; U_i is windspeed on day i; and a = 0, 1, 3, or 6 (0 means no windspeed dependency; 1 means linear dependency, etc.).

For each case, ΣQ_i = 100 g (emission for 3 days). Using the Gaussian dispersion model, the downwind air concentration is inversely proportional to windspeed. Thus, χ_{av} is proportional to $Q_1/U_1 + Q_2/U_2 + Q_3/U_3$, where χ_{av} is the average downwind air concentration over the 3 days.

The air concentration for each day (Q_i/U_i) and the average for the 3 days (χ_{av}) have been computed for each windspeed dependency assumption (i.e., a = 0, 1, 3 or 6) and are presented in Table 6. When no windspeed dependency is assumed, the average concentration is 9.7. As stronger dependencies are assumed, the average concentration drops and for the 6th power the average concentration is about one-half of the first case in which the source strength is independent of the wind. This is because even though there is greater air concentration on the high wind day (8 m/sec), the concentration is much less on the 2 days with the

Table 6. The Effects of the Windspeed Dependency of Source Strength on Average Downwind Air Concentrations

		No Dependency		Linear Dependency		Cubic Dependency		6th Power Dependency	
		a = 0 k = 33.3		a = 1 k = 7.14		a = 3 k = 0.171		a = 6 k = 3.8×10^{-4}	
Day	Windspeed	Q_1	Q_1/U_1	Q_1	Q_1/U_1	Q_1	Q_1/U_1	Q_1	Q_1/U_1
1	2 m/sec	33.3	17	14.3	7.14	1.4	0.68	0.02	0.01
2	4 m/sec	33.3	8	28.6	7.14	11.0	2.74	0.8	0.12
3	8 m/sec	33.3	4	57.1	7.14	87.6	10.94	99.2	12.5
	ΣQ	100		100		100		100	
	χ_{av}		9.7		7.14		4.8		4.2

$Q_1 = KU_1^a$

$Q = Q_1 + Q_2 + Q_3 = 100$

$\chi_{av} \alpha \frac{1}{3} \left(\frac{Q_1}{U_1} + \frac{Q_2}{Q_2} + \frac{Q_3}{U_3}\right)$

lower windspeeds and this gives a lower average. The point to be made by this analysis is that when the windspeed dependence of the source is taken into account, the effect on the downwind air concentrations is not large; this, of course, will vary depending on the actual wind distribution, but it is not expected to be much greater than a factor of two or three. It also means that the air concentrations that are calculated assuming the source strength is independent of wind will probably be somewhat higher than those that would result if a wind-dependent source strength were assumed.

This result is fortunate because the incorporation of wind-dependent sources into dispersion models for computing annual average concentrations adds a complexity and data requirement that exceeds the requirements for the desired model.

As previously discussed, Amick et al. (1974) presented a method for accounting for regional variations in mean windspeed. In this approach, the source term Q is constant for a given region (i.e., for a given dispersion calculation) but varies from region to region based on variations in mean windspeed and soil moisture content. We propose to incorporate Amick's approach to account for regional windspeed variations in emission rates even though we find it unnecessary to use a wind-dependent source term in the Gaussian dispersion model.

B. DISPERSION MODELS

1. Evaluation

To find an appropriate dispersion model, we consulted J.A. Tikvart, Chief, Source Receptor Analysis Branch of the Office of Air Planning and Standards, EPA. He recommended the Industrial Source Complex Model (ISC 1979), which can handle multiple point, area, and line sources in urban or rural terrain. It can predict hourly, monthly, or yearly average concentrations. It computes fallout as well as air concentrations of particulates. Although the ISC has more capability than needed, it can be used readily in the restricted modes (e.g., with only one source).

Another model with much the same capability as the ISC is the Oak Ridge Atmospheric Transport Model (ATM). Like the ISC, the ATM handles multiple area sources and can compute annual average air and surface concentrations. This model is currently being used at EPA by the Exposure Evaluation Division, Office of Toxic Substances.

Based on a brief qualitative evaluation of these models, both appear to be satisfactory for use in the waste disposal problem. In addition to one of these computer models, it is recommended that a simplified dispersion model be developed to provide quick order-of-magnitude estimates of the air concentration at specific distances downwind of a waste disposal site. This hand calculator model will assume that the source and receptor are both at ground level. Area sources will be simulated by assuming a point source that is located upwind, thereby yielding a horizontal dispersion that roughly simulates the spread of the area source when the plume arrives at the area source. This approach has been used by other investigators (e.g., USCG 1975) to simulate area sources with minimum computations and it provides fairly good approximation when properly calibrated. This hand calculator model is described below.

2. Description of the Simplified Dispersion Model

By making a few simplifying assumptions, a dispersion model can be derived that will provide reasonably accurate estimates of the downwind particulate concentrations in air (long-term average), yet will be simple enough to be adapted to the hand calculator. This model will be easier to use than the ATM or the ISC and can be used to make quick estimates of the airborne particulate problem in the vicinity of waste disposal sites.

The simplified dispersion model can be derived by making the following assumptions:

a. The emission source and the receptor are at ground level.

b. There is no fallout of the particulates; thus, surface deposition concentrations (ug/m^2) are not computed.

c. To simulate an area source, a virtual point source is placed upwind of the area source so that the plume width (crosswind direction) is the same width as the area source as it passes over the area.

d. Crosswind dispersions are averaged over the width of the sector in the direction of the wind (this is the same assumption that ATM and ISC use to simplify the calculations).

e. Wind frequencies are given by a 16-sector wind rose; a separate wind rose is used for each of five stability classes (i.e., A, B, C, D, and E/F).

Based on these assumptions, the long-term average air concentration (ug/m^3) at a distance from a point source along an azimuth, where θ is one of 16 possible wind directions, is given by:

$$\chi(x,\theta) = \sum_{j=1}^{N_j} \sum_{i=1}^{N_i} \frac{2.03Q\ f_{i,j}(\alpha)}{(\sigma_z)_i\ u_j\ x} \qquad (1)$$

where:

Q = emission rate, ug/sec

$(\sigma_z)_i$ = vertical diffusion parameter for stability class i and distance x, meters

u_j = mean windspeed for class j, m/sec

$f_{i,j}(\alpha)$ = relative frequency of occurrence of stability class i and windspeed class j with wind direction blowing from α and toward θ (i.e., $\theta = \alpha \pm 180$ degrees)

This equation is derived from equation 3.144 in Slade (1968) by setting the height (h) of the source equal to zero and the number of sectors equal to 16, and then averaging over N_i stability classes and N_j windspeeds.

The joint frequency distribution $f_{i,j}$ can be represented as $f_i f_{ij}(\alpha)$ where f_i is the frequency of stability class i and f_{ij} is the frequency of windspeed j coming from the direction α for stability class i. Notice that

$$\sum_{i}^{N_i} f_i = 1 \qquad \sum_{j}^{N_j} f_{ij} = 1$$

Letting $G_i(x) = \frac{2.03}{(\sigma_z)_i \, x}$

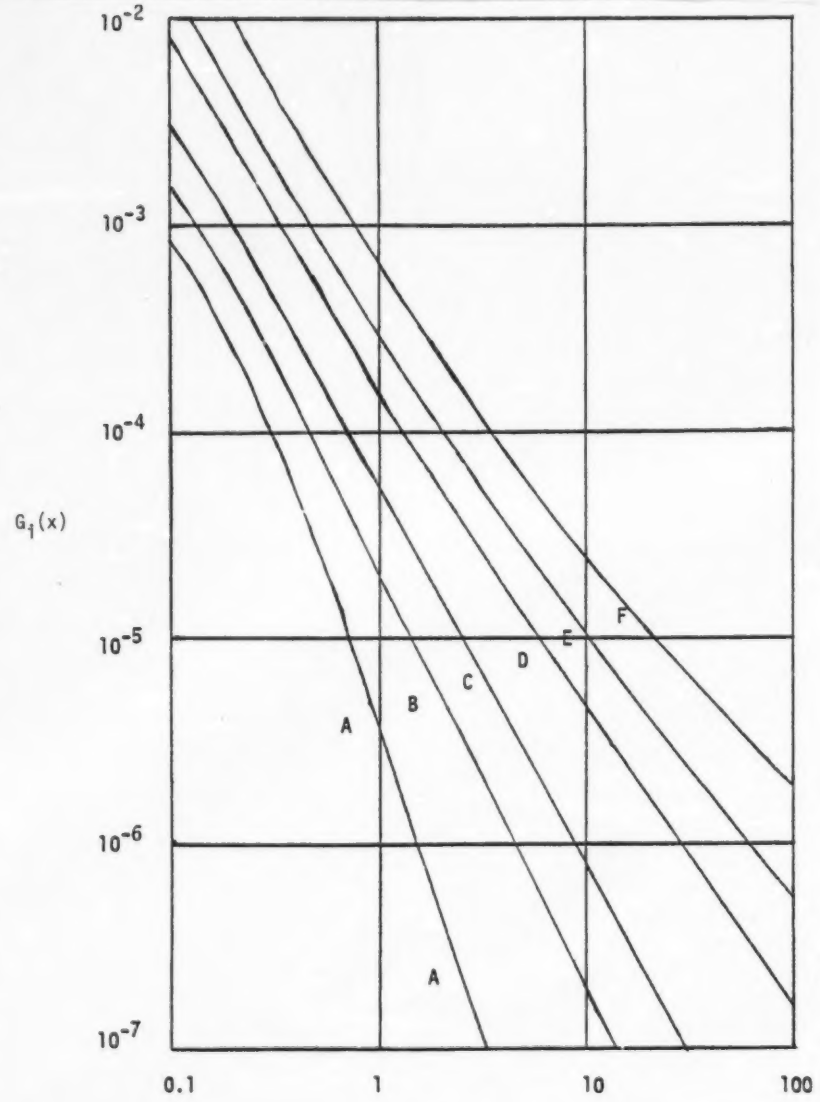
and separating the summations, equation (1) becomes:

$$\chi(x,\theta) = Q \sum_{i}^{N_i} G_i(x) \, f_i \sum_{j}^{N_j} \frac{f_{ij}}{u_j} \qquad (2)$$

$G_i(x)$ is a function of x and the stability class and can be obtained from a graph (Figure 3) or can be programmed into a hand calculator.

Equation (2) gives the ground-level, long-term average particulate concentration from a ground-level point source. All that is needed to make the calculation is:

- the average source strength Q (ug/sec)
- wind roses for the location in question, giving the frequency of each stability class and the frequency of each windspeed class in each of 16 sectors
- $G_i(x)$ as obtained from Figure 3.



x = Distance from point source to receptor - km

Figure 3. $G_1(x)$ as a function of downwind distance and stability class over rural terrain.

The procedure for solving equation (2) is as follows:

(1) Select x and Q.

(2) Extract the frequency data for sector θ from the wind roses.

(3) Perform the summation $\sum_{j}^{N_j} \frac{f_{ij}}{u_j}$ for each stability class.

(4) Obtain values of $G_i(x)$ for each stability class from Figure 3.

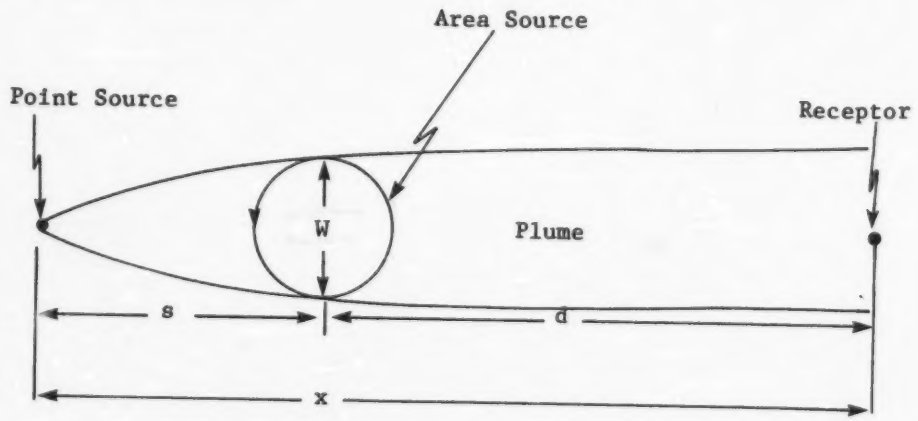
(5) Perform the summation $\sum_{i}^{N_i} G_i(x)\ f_i\ H_i$

where $H_i = \sum_{j}^{N_j} \frac{f_{ij}}{u_j}$ (calculated in step 3 above).

(6) Multiply by Q.

This gives an estimate of the annual concentrations in six simple steps. All summations and operations can be programmed into a hand calculator so all the operator has to do is enter the data in the proper sequence.

Equation (2) is for a point source only. To simulate an area source, we will assume the point source is upwind a distance s from the area source as shown below:



The distance s that results in the plume width equal to the source width is a function of the stability class:

$$s = C_i W$$

where W is the width of the area source and the C_i are given in Table 7.

Table 7. Number of Source Widths the Point Source is Located Upwind

Stability Class	C_i
A	1.17
B	1.61
C	2.40
D	3.57
E/F	6.25

Letting x = d + s and Q = EA, where d is the distance from the area source to the receptor, E is the emission rate in $ug/m^2/sec$, and A is the area of the source in m^2, we have:

$$\chi(d,\theta) = EA \sum_{i}^{N_i} G_i(x) \; f_i \sum_{j}^{N_j} \frac{f_{ij}}{u_j} \qquad (3)$$

Equation (3) estimates the long-term average concentration at a distance d from an area source. The equation is solved in the same way as Equation (2) for a point source except that in determining $G_i(x)$ from Figure 3 (step 4), x is equal to d + s, where s is $C_i W$ (C_i are given in Table 7).

Equation (3) is the recommended simplified dispersion model for waste disposal sites. The data needed to calculate concentrations at distance d and direction θ from a disposal site include:

- Average emission rate (E) in $ug/m^2/sec$
- Wind roses for the locality of interest
- Figure 3 for determining $G_i(x)$
- Table 7 for determining C_i needed to calculate $x = d + C_i W$.

VI. RECOMMENDATIONS

The recommended model for use in predicting annual particulate concentrations in the vicinity of waste disposal sites is the emission rate entrainment model (long-term average) combined with either Oak Ridge's ATM or EPA's ISC model for predicting average annual air and surface concentrations as a function of distance. Both of these dispersion models handle rural terrain, area sources, 16-sector wind rose data, and fallout of the particulates; also, both are fully operational. The decision as to which one to use should probably be based on economics and ease of use, which have not yet been considered. In this regard, features that would be particularly useful are: (1) internal storage of, and access to, wind rose data (making it unnecessary for the user to input the data), and (2) conversational access to the program. We recommend that a quick study be made to compare the models and then to select one on a least-cost/ease-of-use basis.

In addition to the selected computer model that will provide the best available estimates of air and surface concentrations, we recommend the implementation of a simplified dispersion model to provide rough estimates of air concentrations as a function of distance. This model, which does not include deposition or fallout, will provide the capability to make quick calculations to determine if there are potential exposure problems for particular disposal sites and to evaluate the need for more detailed examinations.

To estimate emission rates for waste disposal sites, we recommend that a study be conducted to first characterize waste disposal sites in terms of soil characteristics and activities. All available emission data should then be collected and evaluated with respect to these characteristics. Estimates of long-term average particulate emissions for various types of waste disposal sites should then be made giving consideration to the wind erodibility index to assist in the extrapolation to different types of soil. The use of the wind erosion equation

climatic factor C for modeling regional variations in emission rates, as done by Amick (1974), is recommended. To test the model, air concentrations and surface depositions as a function of distance should be computed for specific sites using the selected dispersion model and appropriate wind rose data.

Although we believe that the extrapolation of existing emission rate data is the best way to model windblown particulate emissions from waste disposal sites in the absence of field measurements, we are not without reservation regarding the accuracy of such a model. Existing emission data are for relatively homogeneous fugitive dust sources, whereas waste disposal sites are expected to be a conglomerate of materials with less predictable behavior and with considerably more variability from site to site. It will be difficult to estimate the effects of these differences, and uncertainties of a factor of 10 or more are possible. Consequently, to calibrate the model and to ensure accuracy of the predictions within acceptable limits, field measurements are recommended for each of the several types of contaminated areas under consideration.

REFERENCES

Amato AJ. 1976. Theoretical resuspension ratios. Proceedings of the International Symposium on Atmosphere-Surface Exchange of Particulate and Gaseous Pollutants, Richland, WA (Sept. 1974), CONF-740921, pp. 891-905.

Amick R, Axetell K, Wells DM. 1974. Fugitive dust emission inventory techniques. Presented at the 67th Annual Meeting of APCA, Denver CO.

Bagnold RA. 1941. The physics of blown sand and desert dunes. Methnen and Co., Ltd., London.

Becker DL, Takle ES. 1979. Particulate deposition from dry unpaved roadways. Atmos. Environ. 13(5):661-668.

Blackwood TR, Chalekode PK, Wachter RA. 1978. Source assessment: crushed stone. EPA-600/2-78-0041. U.S. Environmental Protection Agency.

Blackwood TR, Wachter RA. 1978. Source assessment: coal storage piles. EPA-600-2-78-004k. U.S. Environmental Protection Agency.

Budiansky S. 1980. Dispersion modeling. Environ. Sci. Technol. 14(4):370-374.

Chepil WS. 1945a. Dynamics of wind erosion. II. Initiation of soil movement. Soil Sci. 60:397-411.

Chepil WS. 1945b. Dynamics of wind erosion. III. The transport capacity of the wind. Soil Sci. 60:475-480.

Chepil WS, Woodruff NP. 1963. The physics of wind erosion and its control. Adv. Agron. 15:211-302.

Cole DF, McVehil GE. 1977. Modeling particulate concentrations and dustfall rates at the white rocks sand and gravel mine. 4th International Clean Air Congress Proceedings, Tokyo, Japan. pp. 272-275.

Cowherd C, Axetell K, Guenther CM, Jutze GA. 1974. Development of emission factors for fugitive dust sources. EPA-450/3-74-037. U.S. Environmental Protection Agency.

Cox RA, Shillito DE, Comer PJ, Slater DH. 1977. Novel methods for assessment of air pollution in planning situations where conventional dispersion models are inapplicable. 4th International Clean Air Congress Proceedings, Tokyo, Japan, pp. 923-26.

Culkowsky W, Patterson MR. 1976. A comprehensive atmospheric transport and diffusion model. ORNL/NSF/EAT-17. Oak Ridge National Laboratory.

Davies BE, White HM. 1981. Environmental pollution by wind blown lead mine waste: A case study in Wales, United Kingdom. Sci. Total Environ. 20(1):57-74.

Ellsaesser HW. 1976. Has man, through increasing emissions of particulates, changed the climate? Proceedings of the International Symposium on Atmosphere-Surface Exchange of Particulate and Gaseous Pollutants, Richland, WA (Sept. 1974), CONF-740921, pp. 41-53.

Engelmann RJ. 1976. The relation between soil contamination and lung burden, and implications to resuspension experimental design. Proceedings of the International Symposium on Atmosphere-Surface Exchange of Particulate and Gaseous Pollutants, Richland, WA (Sept. 1974), CONF-740921, pp. 945-959.

Evans JS, Cooper DW. 1980. An inventory of particulate emissions from open sources. J. Air Pollut. Control Assoc. 30(12):1298-1303.

Evans JS, Spedden SE, Cooper DW. 1981. A study of the relationship between wind speed and total suspended particulate levels. J. Air Pollut. Control Assoc. 31(4):395-397.

Fumarola G, Testino S, Ferraiolo G, Mancini R. 1977. Wind erosion of storage piles and dust dispersion in scale model wind tunnel experiments. 4th International Clean Air Congress Proceedings, Tokyo, Japan, pp. 688-690.

Gillette DA. 1974. On the production of soil wind erosion aerosols having the potential for long range transport. J. de Rech. Atmos. 8:735-744.

Gillette DA. 1976. Production of fine dust by wind erosion of soil: Effect of wind and soil texture. Proceedings of the International Symposium on Atmosphere-Surface Exchange of Particulate and Gaseous Pollutants, Richland, WA (Sept. 1974), CONF-740921, pp. 591-609.

Gillette DA, Bifford IH, Fensler CR. 1972. Measurements of aerosol size distributions and vertical fluxes of aerosols on land subject to wind erosion. J. Appl. Meteorol. 11(6):977-987.

Gillette DA, Walker TR. 1977. Characteristics of airborne particles produced by wind erosion of sandy soil, high plains of west Texas. Soil Sci. 123:97-110.

Gillette DA, Porch WM. 1978. Role of fluctuations of vertical and horizontal wind and particle concentration in the deposition of dust suspended by wind. J. Geophys. Res. 83:409-414.

Gryning SE, Larsen SE. 1981. Relation between dispersion characteristics over surfaces with dissimilar roughness and atmospheric stability under conditions of equal geostrophic winds. Atmos. Environ. 15(6):983-987.

Hereim AT, Ritchie B. 1976. Resuspended bacteria from desert soil. Proceedings of the International Symposium on Atmosphere-Surface Exchange of Particulate and Gaseous Pollutants, Richland, WA (Sept. 1974), CONF-740921, pp. 835-845.

ISC. 1979. Industrial Source Complex (ISC) Dispersion Model Users Guide. EPA-450/4-79-030. December 1979.

Jokinen J, Rantakrans, E, Estlander A. 1977. Combining dispersion models and biological effects: Results and perspective. 4th International Clean Air Congress Proceedings, Tokyo, Japan, pp. 633-666.

Lange R. 1978. ADPIC - A three-dimensional particle-in-cell model for the dispersal of atmospheric pollutants and its comparision of regional tracer studies. J. Appl. Meteorol. 17:320-329.

Mills MT, Dahlman RC. Olson JS. 1974. Ground level air concentrations of dust particles downwind from a tailings area during a typical windstorm. ORNL-TM-4375. Oak Ridge National Laboratory.

Momeni MH, Yuan Y, Zielen AJ. 1979. The uranium dispersion and dosimetry (UDAD) code. NUREG/CR-0553 and ANL/ES-72. Argonne National Laboratory.

Ochsner JC, Blackwood TR. 1977. Fugitive emissions from chemical fertilizer mining. Presented at the 2nd Symposium on Fugitive Emissions: Measurement and Control, Houston, TX.

PEDCo. Environmental Specialists. 1973. Investigation of fugitive dust sources, emissions and control. APTD-1582.

Popendorf W. 1980. Exploring citrus harvesters' exposure to pesticide contaminated foliar dust. Am. Ind. Hyg. Assoc. J. 41(9):652-659.

Porch WM. 1973. Recent studies of the suspension of desert dust and resuspension of toxic aerosol due to wind. Livermore, CA: Lawrence Livermore Laboratory, University of California, 19 pp.

Porch WM. 1979. Resuspension of toxic aerosol using MATHEW-ADPIC wind field-transport and diffusion codes. Livermore, CA: Lawrence Livermore Laboratory, University of California, 27 pp.

Reynolds BW, Slinn WGN. 1979. Experimental studies of resuspension and weathering of deposited aerosol particles. Corvallis, OR: Air Resources Center, Oregon State University. NTIS No. SR-0980-5, 102 pp.

Rosinski J, Langer G, Nagamoto CT, Bogard JS. 1976. Generation of secondary particles from single large soil particles. Proceedings of the International Symposium of Atmosphere-Surface Exchange of Particulate and Gaseous Pollutants, Richland, WA (Sept. 1974), CONF-740921, pp. 638-647.

Schwendiman LC, Sehmel GA, Horst GW, Thomas CW, Perkins RW. 1979. A field and modeling study of windblown particles from a uranium mill tailings pile. NUREG/CR-0629 or PNL-2890. Battelle-Pacific Northwest Laboratory.

Sehmel GA. 1980. Particle resuspension: A review. Environ. Inter. 4:107-127.

Sehmel GA, Lloyd FD. 1976. Particle resuspension rates. Proceedings of the International Symposium on Atmosphere-Surface Exchange of Particulate and Gaseous Pollutants, Richland, WA (Sept. 1974), CONF-740921, pp. 846-858.

Sherman CA. 1978. A mass-consistent model for wind fields over complex terrain. J. Appl. Meteorol. 17:312-319.

Skidmore EL. 1976. A wind erosion equation: Development, application, and limitations. Proceedings of the International Symposium on Atmosphere-Surface Exchange of Particulate and Gaseous Pollutants, Richland, WA (Sept. 1974), CONF-740921, pp. 452-465.

Skidmore EL, Woodruff NP. 1968. Wind erosion forces in the United States and their use in predicting soil loss. Agricultural Handbook No. 346, U.S. Department of Agriculture.

Slade DH. 1968. Meteorology and atomic energy. U.S. Atomic Energy Commission.

Slinn WGN. 1976. Dry deposition and resuspension of aerosol particles - a new look at some old problems. Proceedings of the International Symposium on Atmosphere-Surface Exchange of Particulate and Gaseous Pollutants, Richland, WA (Sept. 1974), CONF-740921, pp. 1-40.

Smit P. 1980. Dust concentrations around coal stockpiles. Sci. Total Environ. 15(3):207-216.

Smith WJ II, Whicker FW, Meyer HR. 1982. A review and categorization of saltation, suspension, and resuspension models. Nuclear Safety 23(6), in press.

Travis JR. 1975. A model for predicting the redistribution of particulate contaminants from soil surfaces. LA-6035-MS. Los Alamos, NM: Los Alamos Scientific Laboratory, University of California, 63 pp.

Travis JR. 1976. A model for predicting the redistribution of particulate contaminants from soil surfaces. Proceedings of the International Symposium on Atmosphere-Surface Exchange of Particulate and Gaseous Pollutants, Richland, WA (Sept. 1974), CONF-740921, pp. 906-944.

Turner DB. 1970. Workbook of atmospheric dispersion estimates. Publ. No. Ap-26. U.S. Environmental Protection Agency.

USCG. 1975. Vulnerability model—a simulation system for assessing damage resulting from marine spills. Enviro Control, Inc. June 1975. NTIS AD-A015245.

Wilson L. 1975. Application of wind erosion equation in air pollution surveys. J. Soil & Water Conserv. 30:215-219.

Woodruff NP, Siddoway FH. 1965. A wind erosion equation. Soil Sci. Soc. Amer. Proc. 29:602-608.

Zenchelsky ST, Delany AC, Picket RA. 1976. The organic component of wind-blown soil aerosol as a function of wind velocity. Soil Sci. 122(3):129-132.

Zimmer R, Axetell K. 1978. Fugitive emissions from western surface coal mines. Presented at the 71st Annual Meeting of APCA, Houston, TX.